Quantifying the Effect of Non-Physical Parameters on the Nonlinear Dynamics of an Electromechanical Ratcheting Mechanism

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Abstract

Complex electromechanical mechanisms are found across many industries, from mechanical watches to aerospace applications, and often must account for a multitude of physics and nonlinear phenomena to operate properly. The types of interactions can include friction, contact, and electro-magnetic forces, among others. Given the number of sub-components within a mechanism and the complex nonlinear interactions between parts, it can be challenging to use finite element models (FEMs) to obtain accurate predictions of mechanism's transient response. In particular, numerical studies have indicated that the response of rotating parts is highly sensitive to non-physical model parameters, including mesh resolution, contact algorithm settings, and mesh discretization across processors. While numerous analyses with different FEMs have demonstrated a strong sensitivity to non-physical parameters, it has not been possible to isolate the contribution that each feature of the model contributes to this sensitivity. This work seeks to isolate each model feature's contribution to the larger FEMs sensitivity to non-physical parameters. This is done by creating various sub-models that isolate individual model features (i.e., contact between particular parts, response of helical springs, etc.) to quantify the sensitivity associated of each model feature with the goal of isolating the core model features that result produce the greatest sensitivity to non-physical parameters. In addition to the finite element sub-models, the response of idealized sub-models is compared to the FEM results to assess the appropriateness of simplifying assumptions in the finite element model.

Keywords: Mechanisms, Model Verification, Friction and Contact, Sensitivity Study

1 Introduction

A mechanical watch with a Swiss level escapement/movement relies on a robust system of multiple pawls, gears, and springs to accurately measure time. Xu et. al. noted that the timekeeping accuracy of this movement is heavily reliant on the push of the pallet fork and the swing of the balance wheel [1] . The operation of a one second tick can be separated into three phases: (1) unlock, (2) impulse, and (3) drop. During unlock, the pin rotates the pallet fork causing it to hit the escape wheel. Similar to an impulse hit, the balance wheel rotates from the impact on the escape wheel from the pallet fork. During phase 3, the exit pallet jewel hits the escape wheel, causing it to advance one tooth [2] . This process is then repeated for every second, resulting in that familiar ticking noise. However, this movement can be easily disrupted by shocks and impacts due to the small scale of the components. As a result, significant modeling and testing has been done to add shock mitigation to the movements, including the addition of spring-suspension systems to absorb impact.

When using finite element analysis (FEA) to analyze the Swiss movement with shock mitigation techniques, it is essential to understand the part rotations and interactions between the components, e.g. contact, friction, viscous damping, etc. However, as with most finite element models, non-physical parameters such as mesh size, implicit/explicit analysis, full/reduced time integration, and mesh faceting among others, can add large variances in the outputs of the analysis. One example that has been well studied is finite element model mesh convergence, noting that there is a tradeoff between a finer mesh to yield more accurate results at the cost of computational time. Similarly, better quality meshes and using the correct element formulation for the problem can provide more accurate results [3]. Another area of study is modeling contact, wear, and friction in rotating bodies. The geometry, tolerancing, and gaps between contacting bodies will all affect the impact behavior of those bodies, which inherently changes the kinematic responses of those bodies [4–6]. The third area of interest is the effect of mesh discretization across processors on analysis output. A common way to accelerate the computation speed of an FEA simulation is to use parallel computing. Using more computing processors to parallelize the computation offers a certain speed-up with diminishing returns if the computation is not completely parallelizable [7]. It is worth exploring the effect of minute change in mass and stiffness matrices caused by mesh being divided up between processors on the finite element solutions.

2 Methods

In this work, the effect of non-physical parameters was examined on parts of a ratcheting mechanism similar to a watch movement as shown in Fig. 1. This mechanism consists of a drive arm (akin to a pallet fork), drive pawl (akin to the exit pallet jewel), a hold pawl to stop back rotation, and a ratchet wheel (akin to the escape wheel). A solenoid is used to move the drive arm, thus causing the ratcheting wheel to move. Springs are used to control the rotation of the parts and to bring the system back to a static equilibrium state when not being actuated.

The submodel investigation presented here focused around the hold pawl of the ratcheting mechanism. The hold pawl was then divided into three submodels to further simplify the problem: pin-spring-paw, pin-pawl and pawl-gear as shown in Fig. 2. The isolated feature that was explored in each submodel is spring dynamics, pin joint, and contact between gear tooth and pawl, respectively. The Sierra/Solid Mechanics (Sierra/SM) finite element software was used for the finite element model representation of the submodel.

For each submodel, three model parameters were varied to address the areas of study mentioned before: mesh density, momentum balance iteration, and processor count, as shown in Table 1. The mesh density was changed by varying the mesh element size to 50%, 100%, 150% and 200% of the nominal size. These are respectively listed as fine, nominal, coarse, and very coarse in the table and results. For efficiency, only the mesh at contacting surfaces were changed. For the pin-spring-pawl model, the surfaces where the spring ends contact the pin and pawl, for the pin-pawl model, the cylindrical surfaces where the pin and pawl made contact, and for the pawl-gear model, the contact surfaces between the gear and pawl were subject of mesh density change. In Sierra/SM software, the momentum balance iteration is the number of iterations used to apply forces on the interpenetrating surfaces until the surfaces are no longer in contact [8]. It should be noted that as the number of iterations increases, the accuracy of contact enforcement increases, but the computational expense also increases. The default number of iterations is 5. In this work, this number was varied from 1 to 100. Lastly, the number of processors used for each simulation was varied from 50% to 250% of the nominal processor count. The nominal processor count was decided on the basis of 8000 elements per processor. In addition to FEA, idealized models were developed to verify the FEA results as shown in Fig. 2. Idealized models are simplified versions of the submodels which were calculated using the ode45 solver in MATLAB.

Parameter	Set of Values
Mesh Density	Fine, Nominal, Coarse, Very Coarse
Momentum Balance Iteration	1, 5, 10, 20, 50, 75, 100
Processor Count	50%, 100%, 150%, 200%, 250%

Table 1: Set of non-physical parameters

A sensitivity study of these non-physical parameters were performed for two different input loads applied to the sub-models, namely haversine shock loads and sinusoidal vibrations. For the pin-spring-pawl model, the pawl was displaced along the axial direction of the spring while the base of the pin was fixed in all directions. In the pin-pawl submodel, pressure was applied to the side of the pawl to induce rotation, a constant seating force was applied in one direction to prevent excessive rotation, and the base of the pin was fixed in all directions. For the pawl-gear submodel, the ratchet wheel was displaced in the

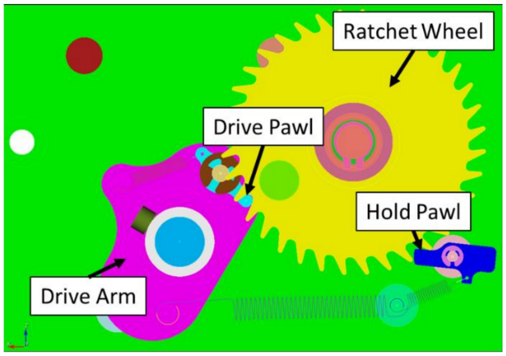

Figure 1: Ratcheting Mechanism

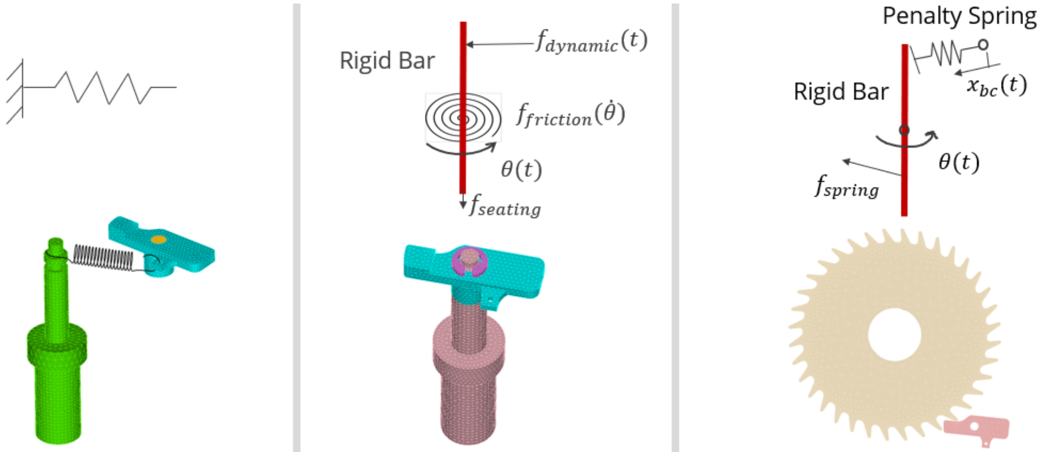

Figure 2: Idealized (top) and FE model (bottom) of pin-spring-pawl (left), pin-pawl (center), and pawl-gear (right) submodel

negative vertical direction, the pawl was fixed in radial and axial directions, and a pseudo spring force was applied in the spring direction. Different values of amplitude and frequency of the two inputs were used for each submodel as their response varied significantly. Each submodel had a specific output that was deemed the quantity of interest. For the pin-spring-pawl submodel, the quantities of interest were the contact forces from the spring to the pin and pawl. For the pin-pawl submodel, the quantities of interest were the contact force between the pin and pawl, and the pawl rotation angle. Lastly, for the pawl-gear submodel, the quantity of interest was the pawl rotation.

3 Results

Each submodel exhibited different levels of sensitivity to the three non-physical parameters. The pin-spring-pawl submodel did not exhibit any sensitivity to all three parameters. The results for mesh density is shown in Fig. 3. The results for momentum balance iteration and processor count showed similar responses. The idealized model exhibits the model's response only during the haversine pulse and smaller amplitude for sinusoidal input. This is expected as the idealized model does not take into account any of the dynamic response of the spring. For the pin-pawl submodel, significant sensitivity was observed for mesh density and momentum balance iteration. The response to the latter parameter is shown in Fig. 4. The submodel showed similar response to mesh density. For processor count, submodel's response did not change significantly in haversine shock, but did change in sinusoidal vibration just like the other two parameters. The idealized model of the pin-pawl submodel agrees with the overall profile of the response in FEA, but requires further improvement as the closest value in FEA for the momentum balance iteration is of 1 which is the least accurate for contact enforcement. Lastly, the pawl-gear submodel is significantly sensitive to moemntum balance iteration and mesh density in sinusoidal vibration, but not in haversine pulse. In addition, change in processor count did not affect the results for both environments. Similar to the pin-pawl submodel, the idealized model follows a similar trend, but not exactly the same, which is an area of improvement that can be worked on in the future.

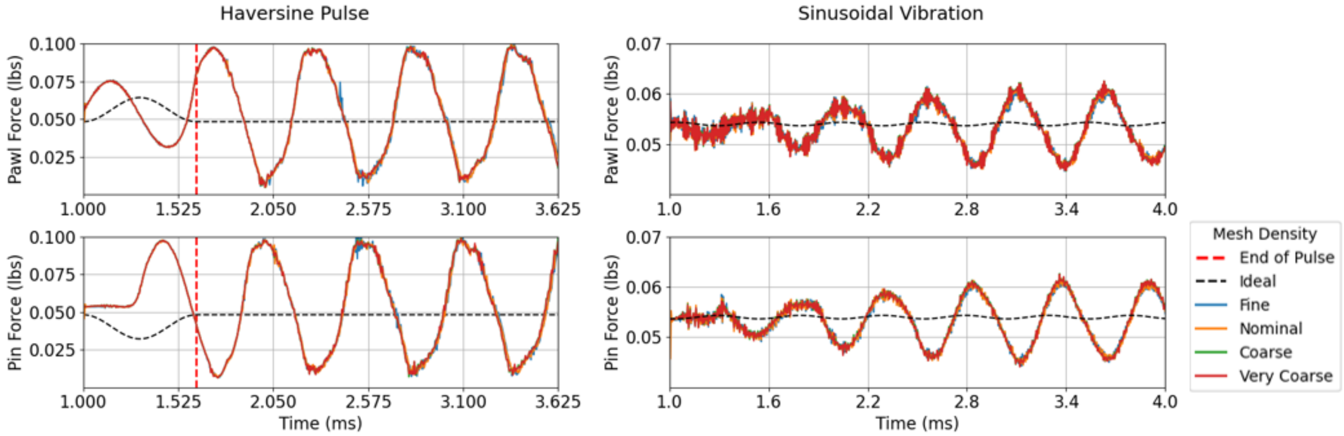

Figure 3: Pin-spring-pawl submodel's pin and pawl force sensitivity to mesh density

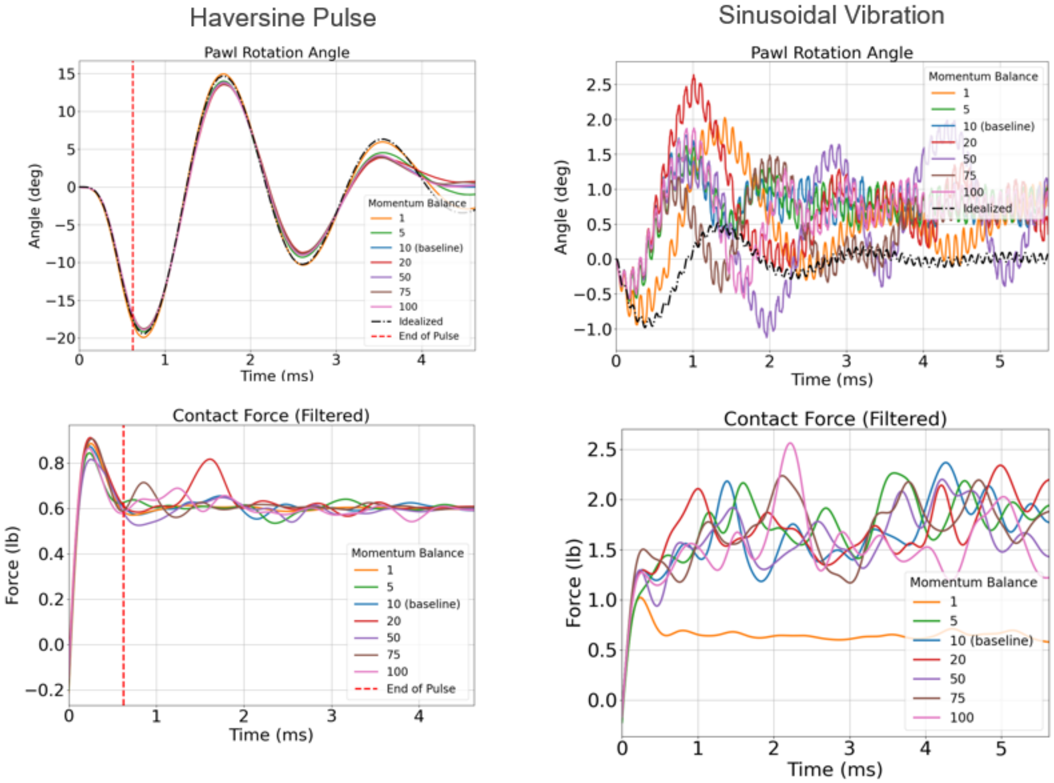

Figure 4: Pin-pawl submodel's pawl rotation and contact force sensitivity to momentum balance iteration

4 Conclusion

The parametric study of non-physical parameters including momentum balance iteration, mesh density and processor count used has revealed the sensitive nature of the FE model at the submodel-level of the ratcheting mechanism. Different levels of sensitivity were observed across the three submodels; the pin-spring-pawl submodel is not sensitive to any of the three parameters, while the pin-pawl submodel is sensitive to all but the processor count in the shock environment, and the pawl-gear submodel is sensitive to momentum balance iteration and mesh density in the vibration environment. The results suggest that for a model similar to the pin-spring-pawl submodel, the parameters can be optimized for accuracy or computational cost, but for a model similar to the pin-pawl and pawl-gear submodel that include significant amount of contact and friction, changing the parameters requires extra attention. Therefore, the results affirm the complexity of a ratcheting mechanism and modeling consideration required for such mechanism in FEA. Future work will include combing the submodels and studying the change

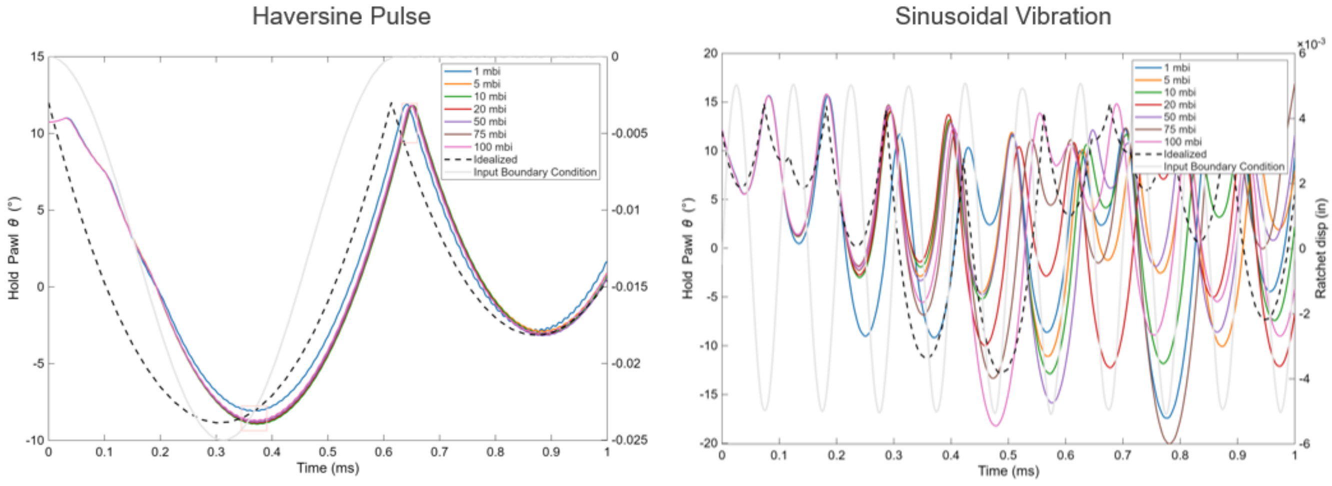

Figure 5: Pawl-gear submodel's pawl rotation sensitivity to momentum balance iteration

in the effect of the non-physical parameters, studying other non-physical parameters for further investigation, and performing similar study on the drive pawl and extending the study to the assembly level.

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